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CONSTRAINTS ON THE PROTON'S GLUON DENSITY FROM LEPTON-PAIR PRODUCTION

EDMOND L. BERGER
High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
E-mail: berger@anl.gov

M. KLASEN
II. Institut für Theoretische Physik, Universität Hamburg, D-22761 Hamburg, Germany
E-mail: michael.klasen@desy.de

Massive lepton-pair production, the Drell-Yan process, should be a good source of independent constraints on the gluon density, free from the experimental and theoretical complications of photon isolation that beset studies of prompt photon production. We provide predictions for the spin-averaged and spin-dependent differential cross sections as a function of transverse momentum Q_T.

1 Introduction

Massive lepton-pair production, $h_1 + h_2 \to \gamma^* + X; \gamma^* \to l\bar{l}$, the Drell-Yan process, and prompt real photon production, $h_1 + h_2 \to \gamma + X$, are two of the most valuable probes of short-distance behavior in hadron reactions. They supply critical information on parton momentum densities and opportunities for tests of perturbative quantum chromodynamics (QCD). Spin-averaged parton momentum densities may be extracted from spin-averaged nucleon-nucleon reactions, and spin-dependent parton momentum densities from spin-dependent nucleon-nucleon reactions.

The Drell-Yan process has tended to be thought of primarily as a source of information on quark densities. Indeed, the mass and longitudinal momentum (or rapidity) dependences of the cross section (integrated over the transverse momentum Q_T of the pair) provide essential constraints on the *antiquark* momentum density, complementary to deep-inelastic lepton scattering from which one gains information of the sum of the quark and antiquark densities. Prompt real photon production, on the other hand, is a source of essential information on the *gluon* momentum density. At lowest order in perturbation theory, the reaction is dominated at large values of the transverse momentum p_T of the produced photon by the QCD "Compton" subprocess, $q + g \to \gamma + q$. This dominance is preserved at higher orders, indicating that the experimental inclusive cross section differential in p_T may be used to determine the density of gluons in the initial hadrons.

In this contribution, we summarize recent work[1,2], in which we demonstrate that the QCD Compton subprocess, $q+g \to \gamma^*+q$ also dominates the Drell-Yan cross section in polarized and unpolarized proton-proton reactions for values of the transverse momentum Q_T of the pair that are larger than roughly half of the pair mass Q, $Q_T > Q/2$. Dominance of the qg contribution in the massive lepton-pair case is as strong if not stronger than it is in the prompt photon case. Massive lepton-pair differential cross sections are therefore an additional useful source of constraints on the the spin-averaged and spin-dependent *gluon densities*. Although the cross section is smaller than the prompt photon cross section, massive lepton pair production is cleaner theoretically since long-range fragmentation contributions are absent as are the experimental and theoretical complications associated with isolation of the real photon. As long Q_T is large,

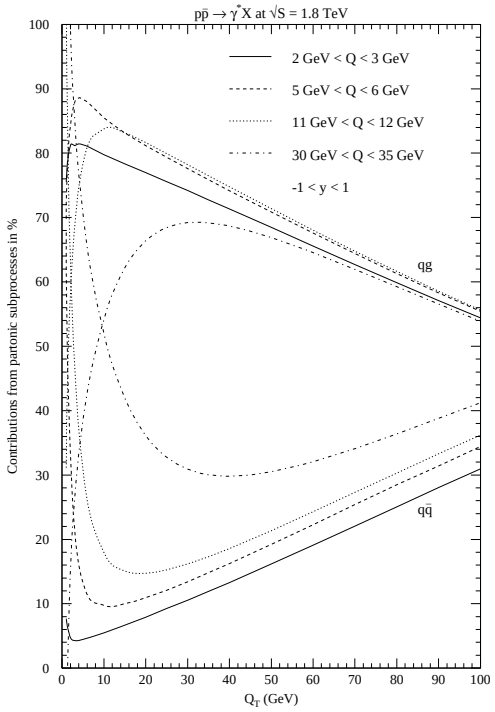

Figure 1. Contributions from the partonic subprocesses qg and $q\bar{q}$ to the invariant inclusive cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $p\bar{p} \to \gamma^* X$ at $\sqrt{S} = 1.8$ TeV.

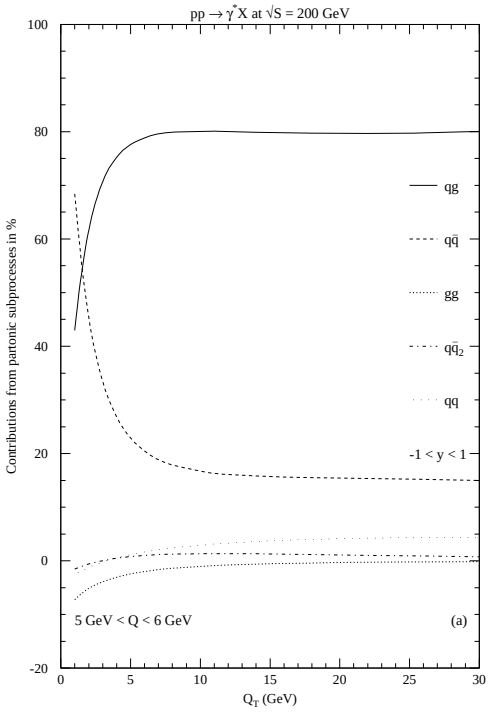

Figure 2. Contributions from the partonic subprocesses qg and $q\bar{q}$ to the invariant inclusive cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $pp \to \gamma^* X$ at $\sqrt{S} = 200$ GeV.

the perturbative requirement of small $\alpha_s(Q_T)$ can be satisfied without a large value of Q. We therefore explore and advocate the potential advantages of studies of $d^2\sigma/dQdQ_T$ as a function of Q_T for modest values of Q, $Q \sim 2$GeV, below the range of the traditional Drell-Yan region.

2 Unpolarized Cross Sections

For $p\bar{p} \to \gamma^* + X$ at $\sqrt{S} = 1.8$ TeV and several values of the mass of the lepton-pair, we present in Fig. 1 the $q\bar{q}$ and qg perturbative contributions to the invariant inclusive cross section $Ed^3\sigma/dp^3$ as a function of Q_T. For small Q_T, the $q\bar{q}$ contribution exceeds that of qg channel. However, as Q_T grows, the qg contribution becomes increasingly important and accounts for 70 to 80 % of the rate once $Q_T \simeq Q$. (The $q\bar{q}$ contribution begins to be felt a second time at very large Q_T owing to the valence nature of the $\bar{q}$ density in the $\bar{p}$.) Subprocesses other than those initiated by the $q\bar{q}$ and qg initial channels contribute negligibly.

Prompt photons have been observed in Fermilab Tevatron collider experiments with values of p_T extending to 100 GeV and beyond. Lepton-pair cross sections are smaller owing to the factor $\alpha_{em}/(3\pi Q^2)$ associated with the decay of the virtual photon to $\mu^+\mu^-$. It should be possible to examine massive lepton-pair cross sections in the same data sample out to Q_T of 30 GeV or more. The statistical limitation to Q_T of about 30 GeV means that the reach in x_{gluon}, the fractional light-cone momentum carried by the incident gluon, is limited presently to $2Q_T/\sqrt{S} \sim 0.033$, a factor of three less than that potentially accessible with prompt photons. It is

valuable nevertheless to investigate the gluon density in the region $x_{gluon} \sim 0.033$, and less, with a process that has reduced experimental and theoretical systematic uncertainties from those of the prompt photon case.

In Fig. 10 of the first paper[1], we show a comparison with data of our calculated invariant inclusive cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $p + \bar{p} \to \gamma^* + X$, with $\gamma^* \to \mu^+\mu^-$, at $\sqrt{S} = 630$ GeV, with $2m_\mu < Q < 2.5$ GeV. The theoretical expectation is in good agreement with the data published by the CERN UA1 collaboration[3]. Dominance of the qg component is evident over a large interval in Q_T. It would be valuable to make a similar comparison with Tevatron data.

Results similar to those above are shown in Fig. 2 for $pp \to \gamma^* + X$ at $\sqrt{S} = 200$ GeV appropriate for the RHIC collider at Brookhaven. The fraction of the cross section attributable to qg initiated subprocesses again increases with Q_T, growing to 80 % for $Q_T \simeq Q$. Predictions of spin-averaged and spin-dependent cross sections for the energies of the RHIC collider may be found in the second paper[2]. Adopting the nominal value $Ed^3\sigma/dp^3 = 10^{-3}\text{pb/GeV}^2$, we establish that the massive lepton-pair cross section may be measured to Q_T =14 and 18.5 GeV in $pp \to \gamma^* + X$ at $\sqrt{S}$ =200 and 500 GeV, respectively, when $2 < Q < 3$ GeV, and to Q_T =11.5 and 15 GeV when $5 < Q < 6$ GeV. In terms of reach in x_{gluon}, these values of Q_T may be converted to $x_{gluon} \simeq x_T = 2Q_T/\sqrt{S} = 0.14$ and 0.075 at $\sqrt{S} =$ 200 and 500 GeV when $2 < Q < 3$ GeV, and to $x_{gluon} \simeq 0.115$ and 0.06 when $5 < Q < 6$ GeV. The smaller cross section in the case of massive lepton-pair production means that the reach in x_{gluon} is restricted to a factor of about two to three less, depending on $\sqrt{S}$ and Q, than that potentially accessible with prompt photons in the same sample of data.

In the first paper[1], we compare our spin-averaged cross sections with fixed-target data on massive lepton-pair production at large values of Q_T, and we establish that fixed-order perturbative calculations, without resummation, should be reliable for $Q_T > Q/2$.

Although the qg Compton subprocess is dominant, one might question whether uncertainties associated with the quark density compromise the possibility to determine the gluon density. In this context, it is useful to recall[4] that when the Compton subprocess is dominant, the spin-averaged cross sections for prompt photon production and for lepton-pair production may be rewritten in a form in which the quark densities do not appear explicitly, but, instead, directly in terms of the proton structure function $F_2(x, \mu_f^2)$ *measured* in spin-averaged deep-inelastic lepton-proton scattering. An analogous statement applies in the spin-dependent case where the lepton pair cross section may be expressed in terms of the $g_1(x, \mu_f^2)$ structure function measured in spin-dependent deep-inelastic lepton-proton scattering.

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References

1. E. L. Berger, L. E. Gordon, and M. Klasen, *Phys. Rev.* D **58**, 074012 (1998) and *Nucl. Phys. Proc. Suppl.* **82**, 179 (2000).
2. E. L. Berger, L. E. Gordon, and M. Klasen, *Phys. Rev.* D **62**, 014014 (2000) and hep-ph/0001190.
3. CERN UA1 Collaboration, C. Albajar *et al*, *Phys. Lett.* B**209**, 397 (1988).
4. E. L. Berger and J.-W. Qiu, *Phys. Rev.* D **40**, 778 (1989) and D **40**, 3128 (1989).